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PHYSICAL CONDITIONS IN LIMB FLARES AND ACTIVE PROMINENCES. VI. SELECTIVE EXCITATION CONDITIONS

N63 17903

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Reprinted for private circulation from
THE ASTROPHYSICAL JOURNAL
Vol. 137, No. 1, January 1963

17903

PHYSICAL CONDITIONS IN LIMB FLARES AND ACTIVE PROMINENCES

VI. SELECTIVE EXCITATION CONDITIONS

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Received February 7, 1962; revised July 6, 1962

ABSTRACT

The complex surge prominence of November 18, 1960, is studied spectroscopically. It is shown that the surge consists of different regions, where the physical conditions (temperature and/or internal motions) differ from one region to another. The metal and helium regions are shot out from an underlying flare in different directions. We notice that the emission from Fe II is considerably fainter than that from Ti II or Ba II.

A finer spectroscopic classification of flares and prominences than that previously introduced is discussed. We find, as a general rule, that while Ti II lines are stronger than Fe II lines in prominences, the reverse holds true in flares. As a new classification criterion we introduce the line-intensity ratio $M = [I(\text{Fe II}, 4584)/I(\text{Ti II}, 4572)]$.

I. INTRODUCTION

In the first paper of this series (Tandberg-Hanssen and Zirin 1959, hereafter called "Paper I") we concluded that active prominences were built up of regions of different temperatures and that the different line emissions (from He II, He I, and H I) originated in these different temperature regions. A spectral classification system for prominences was discussed in Paper IV of the series (Zirin and Tandberg-Hanssen 1960). This classification, whose virtue is its simplicity, suffices to divide prominences into two major categories: active prominences (and flares) and quiescent prominences. There seem, however, to be reasons for introducing finer classification details, and we shall discuss this in Section V.

In the first sections we shall derive the excitation conditions in a well-observed surge of November 18, 1960. This apparently "semiactive" prominence proved to be especially well suited for a closer study of the selective excitation conditions found in several objects of this, or a similar, kind. We also present new evidence that surges consist of different temperature regions.

II. DESCRIPTION OF THE NOVEMBER 18, 1960, SURGE

On November 18, 1960, at about 2020 U.T., a brilliant surge appeared at the sun's west limb, and a set of high-dispersion spectra (2.7 A/mm) was obtained at 2032 U.T. with the 5-inch coronagraph and the grating spectrograph of the Climax station. Figure 1 shows the development of the surge, which was described as a "limb flare–surge" by the observers. The surge appeared in active region No. 5927 (McMath-Hulbert Observatory numeration) which crossed the central meridian on November 12. At 2020 U.T. on November 18, an importance 2 flare was reported, and this flare, which was considered terminated at 2030 U.T., apparently triggered the surge.

Figure 2 reproduces a sample spectrum of the 4500 A region, taken with a curved slit parallel to the sun's limb. The actual height above the photosphere is difficult to ascertain. It is about 10000 km, and in the following we shall assume it to be so and give all the other heights relative to this level. The exposure time was 25 seconds on 35-mm Kodak Plus-X film. Two sets of emission features, A and B, are clearly seen separated in the metal lines, but not in the helium lines (or in the overexposed hydrogen line). A closer study reveals the important fact that the metal lines from position angle A display strong

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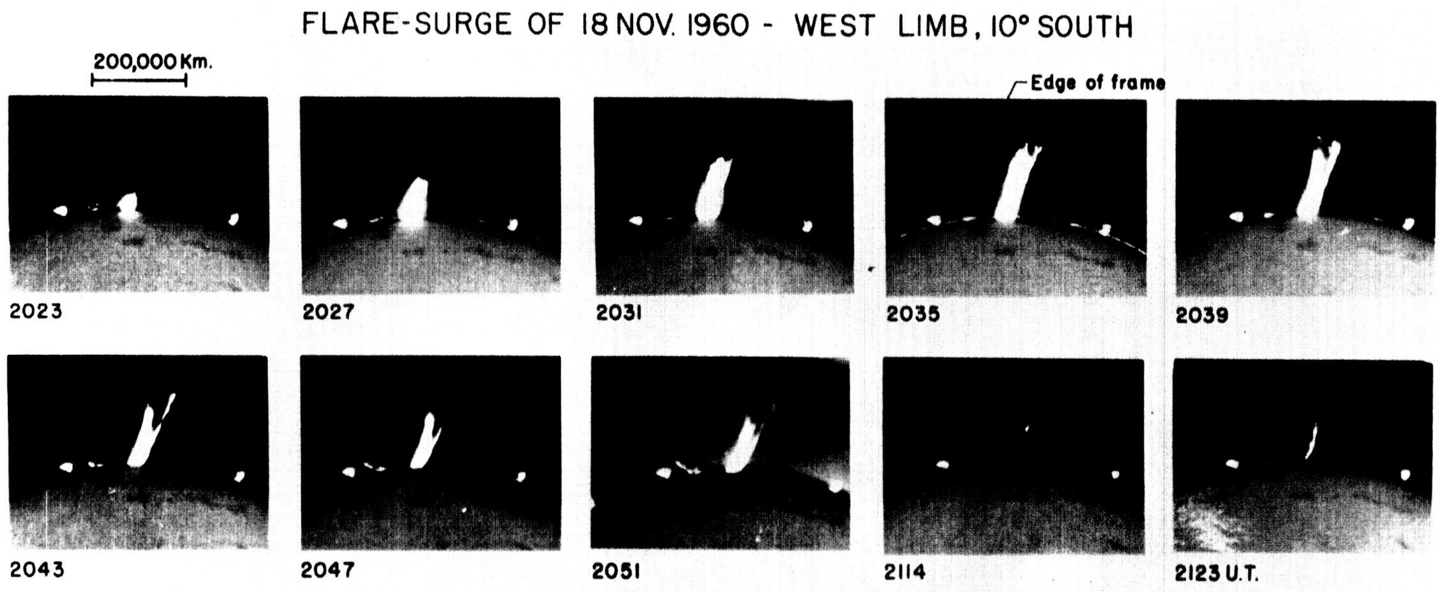

FIG. 1.—Hα patrol photographs of the surge prominence of November 18, 1960

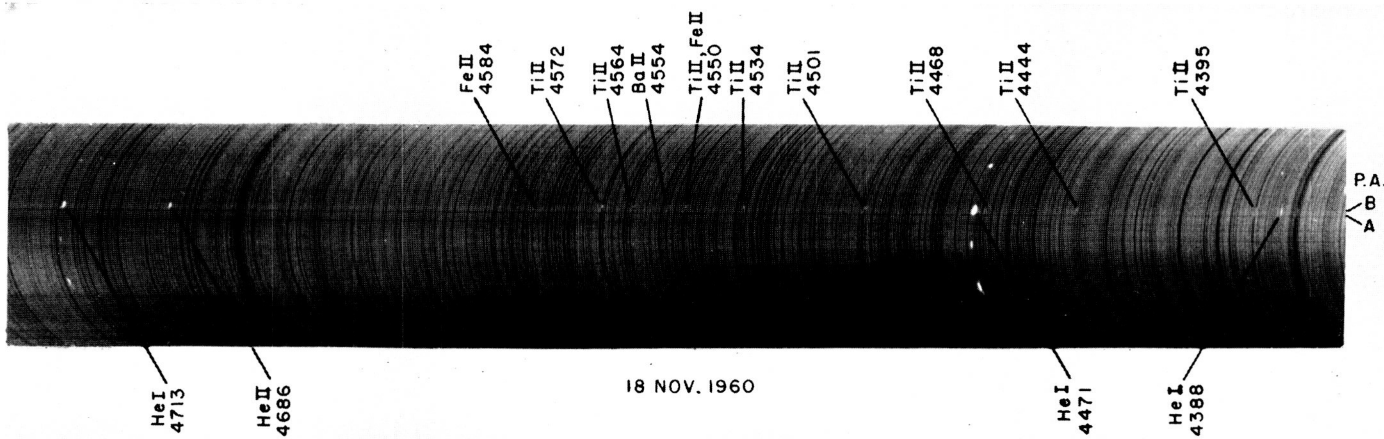

Fig. 2.—Spectrum in the blue-green region of the surge of November 18, 1960

Doppler motions (toward longer wavelengths) which decrease with height and are not paralleled by the helium lines.

The surge thus consisted of two parts, and we have measured the velocity at right angles to the line of sight (from the Hα patrol films) and the line-of-sight velocity (from the Doppler displacements). The composite picture obtained is that of a surge, shot out of a flare at a velocity greater than 200 km/sec. One part, *B*, starts out in a direction perpendicular to the line of sight. Part *A* starts out in a direction that makes an angle of approximately 70° with the line of sight (Doppler motion corresponding to some 50 km/sec) and then curves toward the earth until it flows out in a direction perpendicular to the line of sight.

III. EMISSION-LINE INTENSITIES AND HALF-WIDTHS

The following prominence lines are seen in emission in the spectral region 4350–4880 A (see Table 1). The Ti II, 4550 line (multiplet 82) blends with the Fe II, 4550 line of multiplet No. 38. The other line of multiplet 38 in this wavelength region (at 4584 A) is very faint, and we conclude that the observed emission at 4550 A is due mainly to the Ti II line. Multiplet 82 of Ti II thus represents the strongest metal lines in our spectra. The absence or weakness of the Fe II lines of multiplets Nos. 37 and 38, relative to the Ti II lines (multiplets 31, 50, and 82) is quite remarkable. A study of this and other selective excitation conditions will be presented in Section V.

TABLE 1

EMISSION LINES IN THE SURGE PROMINENCE OF NOVEMBER 18, 1960

No.	λ	Identification		Excitation Potential (ev)	Ionization Potential (ev)	Remarks
		Ion	Multiplet			
1......	4861	H I	1	12.69	13.6	Hβ, overexposed
2......	4388	He I	51	23.94	24.58	
3......	4471	He I	14	23.63	....	
4......	4713	He I	12	23.49	....	"Classification line"
5......	4686	He II	1	24.58+50.8	54.4	"Classification line"
6......	4395	Ti II	19	6.8 + 3.9	13.6	
7......	4444	Ti II	19			
8......	4468	Ti II	31	6.8 + 3.9		
9......	4501	Ti II	31			
10......	4534	Ti II	50	6.8 + 3.9		
11......	4564	Ti II	50			
12......	4550	Ti II	82	6.8 + 4.3		Blend with Fe II
13......	4572	Ti II	82			"Classification line"
14......	4384	Fe I	41	4.3	7.9	Faint
15......	4405	Fe I	41	....	....	Very faint
16......	4550	Fe II	38	7.9 + 5.5	16.2	Blend with Ti II
17......	4584	Fe II	38			Very faint
18......	4554	Ba II	1	5.2 + 2.7	10.0	Resonance line

The only lines from neutral metals (representing low-excitation conditions) observed in the surge are the great arc lines of Fe I, multiplet No. 41, at 4384 and 4405 A. Their presence is an indication of the complexity of the excitation conditions in the solar atmosphere.

From the spectra we see that, below roughly 20000 km above the photosphere, line emission is stronger from part *B* than from part *A*. This applies to hydrogen and helium as well as to the metal lines. There are, however, interesting differences between the helium and the metal-line emission (see Table 2). The helium emission from part *B* fades rapidly with height, while that from part A stays more nearly constant. On the other hand, the metal-line emission stays fairly constant with height in both part A and part B.

All prominence lines showing sufficient emission have been traced at different heights, and their total intensities, $I = I_0 \Delta\lambda$, are given in Table 2, where I_0 is the central intensity and $\Delta\lambda$ is the total width at half-intensity. A number of line profiles have also been studied, and mean Doppler half-widths, $\Delta\lambda_D$, are given in Table 3 for different atomic or ionic species.

The differences in $\Delta\lambda_D$ for position angles A and B may not be significant, in which case they only emphasize the degree of uncertainty involved in this kind of observations (we do not claim an accuracy better than, say, 10 per cent). The differences between the $\Delta\lambda_D$ values for He II, He I, and the metals, on the other hand, are real and of great im-

TABLE 2

RELATIVE LINE INTENSITIES IN SURGE OF NOVEMBER 18, 1960

LINE	HEIGHT (km)						
	Position Angle A			Position Angle B			Top
	8000	17000	27000	8000	17000	27000	40000
He II, 4686	2.5	2.5	1.6	8.5	5.2	1.6	1.0
He I, 4388	1.9	1.8	1.4	3.9	2.5	1.9	....
4471	61	....	60	....	....	5.8	35
4713	(5.2)*	4.2	4.6	15	9.5	4.7	3.2
Ti II, 4395	....	1.4	....	....	2.5	....	....
4444	....	1.3	....	2.3	2.3	....	....
4468	....	1.6	....	1.9	2.3	....	....
4501	1.0	1.6	....	2.8	2.7	....	....
4534	....	2.2	....	2.9	....	....	....
4564	....	....	1.6	....	2.4	....	....
4550	1.3	2.1	....	3.1	4.0	....	....
4572	1.7	2.1	2.0	4.0	3.9	(4.3)	4.4
Fe II, 4584	....	....	(0.8)	....	....	1.3	....
Ba II, 4554	1.3	1.1	(0.2)	1.6	1.4	1.3	(0.9)

* Values in parentheses are less reliable.

TABLE 3

DOPPLER HALF-WIDTHS OF He II, He I, Ti II, AND Ba II LINES IN THE SURGE OF NOVEMBER 18, 1960

ION	POSITION ANGLE B			POSITION ANGLE A
	$\Delta\lambda_D$ (A)	ξ_0 (km/sec)	T (° K)	$\Delta\lambda_D$ (A)
He II	0.41	27	1.56×10^5	0.39
He I	.28	18	7.8×10^4	.29
Ti II	.27	18	9.4×10^5	.25
Ba II	0.19	13	1.43×10^6	0.21

portance. They point to different physical conditions in the regions where the corresponding lines are formed. If the line widths are due entirely to "turbulent" motions, we arrive at the values for ξ_0, given in Table 3, third column. The most probable space velocity, ξ_0, is related to the Doppler width by the equation

$$\xi_0 = \frac{c}{\lambda} \Delta\lambda_D . \quad (1)$$

If, however, the line widths reflect only the thermal motions of the particles, the corresponding kinetic temperatures, T_e, would be those indicated in the fourth column of Table 3. The temperature is given by

$$T_e = \frac{m_H c^2 \mu}{8 k \ln 2} \left(\frac{\Delta\lambda}{\lambda}\right)^2 = 1.95 \times 10^{12} \mu \left(\frac{\Delta\lambda}{\lambda}\right)^2 , \quad (2)$$

where μ is the mass of the atom in question relative to the mass m_H of the hydrogen atom.

There is no way of separating the effects of temperature and "turbulence" on the line widths in the present case, since the spectra clearly point out that the bulk of the helium emission comes from a region different from the metal region. In their work on prominence spectra Jefferies and Orrall (1961) have previously pointed out that rapid internal motions invariably influence the line-widths. We also find that a study of the profiles leaves no doubt that motions strongly influence the helium lines in position angle A at low heights. Here the profiles are quite broad with marked wings. Going up the surge, we encounter narrower profiles (more and more Gaussian) and greater central intensities. The total intensity $I_0\Delta\lambda$ thus remains fairly constant up to and beyond 20000 km (see Table 2).

There is certainly also at position angle B some influence on the line profiles due to "turbulent" motions. That these, however, are not dominant is seen from a study of the metal-line emission. Provided the Ti II and Ba II lines are formed in the same regions, the value of the ratio $(\Delta\lambda/\lambda)^2_{\text{Ba II}}/(\Delta\lambda/\lambda)^2_{\text{Ti II}}$ will depend on whether temperature effects or turbulent motions dominate the formation of the line profiles. In the first case we would have

$$\frac{(\Delta\lambda/\lambda)^2_{\text{Ba II}}}{(\Delta\lambda/\lambda)^2_{\text{Ti II}}} = \frac{m_{\text{Ti}}}{m_{\text{Ba}}} = 0.35 , \quad (3)$$

where m_{Ti} and m_{Ba} are the masses of the Ti II and Ba II ions, respectively. With turbulence dominating, we find, on the other hand,

$$\frac{(\Delta\lambda/\lambda)^2_{\text{Ba II}}}{(\Delta\lambda/\lambda)^2_{\text{Ti II}}} = 1 . \quad (4)$$

Now, for the Ti II, 4572 and the Ba II, 4554 lines actually observed,

$$\frac{(\Delta\lambda/\lambda)^2_{\text{Ba II}}}{(\Delta\lambda/\lambda)^2_{\text{Ti II}}} = 0.5 \text{ to } 0.8 .$$

This ratio indicates that either turbulence, if present, is not important, or that the lines are not formed in the same region.

A closer inspection of the Ba II emission reveals that at the lowest heights in position angle A the 4554 line is as strong as, or stronger than, the 4572 line of Ti II. As one goes up the surge into higher regions, the ratio $I(4572)/I(4554)$ increases rapidly (see Table 4). This same ratio varies less in B, but here also it increases, from a value of about 2 at

6000 km to a value around 4 at 35000 km. We notice, further, from the spectra that this increase is mainly due to a rapid decrease with height of the Ba II emission. This can be interpreted in two possible ways, either (1) as a change in the excitation conditions with height or (2) as an abundance effect, viz., the abundance of barium relative to titanium decreases with height.

In support of the latter explanation, one would have to invoke a diffusive separation. This might be due to a gradient, in the surge, in either temperature, pressure, or concentration. However, a simple plasma-physical discussion shows that such a separation cannot occur; the decisive argument being that the characteristic time for establishing diffusive separation is very much greater than the time during which a flare or surge changes appreciably because of large-scale mass motions.

We are thus left with the first explanation: The variation in the intensity ratio must be due to changing excitation conditions within the metal region. In other active prominences that we have studied, it has not been possible to detect any significant change in the $I(4572)/I(4554)$ ratio with height. The present observation indicates that the conditions within the metal region in an active object may not be so uniform as we have often imagined.

TABLE 4

INTENSITY RATIO [$I(4572)/I(4554)$] AS FUNCTION OF HEIGHT IN SURGE OF NOVEMBER 18, 1960

	Height (km)						
	6000	8000	14500	17000	19000	23500	27000
Position angle *A*	0.9	1.3	(1.3)	1.9	2.0	5.5	(10)
Position angle *B*	1.9	2.5	2.5	2.8	2.4	3.2	(3.3)

The criteria used to characterize prominences as active or quiescent (Papers I and IV) involve (in the wavelength region considered) the lines 4686 A of He II, 4713 of He I, and 4572 of Ti II. A prominence is then termed "active" or "quiescent" according to whether $R = I_0\Delta\lambda(4686)/I_0\Delta\lambda(4713)$ takes a value near unity or is much less than unity and whether the ratio $Q = I_0\Delta\lambda(4713)/I_0\Delta\lambda(4572)$ is much greater than unity or near unity (see also Table 6). In the present case, R is about 0.5, showing a tendency to decrease with height in both position angle A and position angle B. This indicates a spectroscopically "semiactive" prominence. The Q-value is about 2 in position angle A and stays constant with height, while it decreases in position angle B from a value of about 4 to unity as one goes from a height of 8000 to 30000 km. This means that the degree of activity decreases with height, especially in position angle B. Since surges seem to derive their energy from below—being perhaps the superficial manifestation of a much more violent, deeper-lying disturbance—this decrease in activity may be expected. The conditions are notably different for loops, which often seem to condense out of the corona and rain down. In that case, the energy is supplied from above.

IV. DIFFERENT TEMPERATURE REGIONS

The most direct evidence that the helium and the metal lines come from different regions in the surge of November 18, 1960, is furnished by the Doppler displacements. It has already been mentioned that the emission lines from position angle A reveal strong Doppler motions. It should be pointed out that this is by no means unique, but the surge of November 18 is the first prominence we have studied the spectra of which show significantly different motions for the metals and for helium.

We have measured the Doppler displacements of emission lines from position angle A relative to the undisplaced emission lines from position angle B at several heights. If, for any line, we define

$$\delta\lambda = |\lambda(A) - \lambda(B)| , \tag{5}$$

we find the following characteristic displacements (see Table 5). The displacements correspond to line-of-sight velocities v, given by $v = c\delta\lambda/\lambda$.

The difference between the $\delta\lambda$ value for the He II emission and the mean $\delta\lambda$ value for the He I emissions is not significant. The comparatively large value of $\delta\lambda$ for the He I, 4713 line relative to the other helium lines is difficult to explain. The line is fairly strong and easily measurable, and it is hard to believe that the difference is not real, even though the accuracy of the velocity measurements are probably not much better than about 5 km/s. If the difference is significant, it shows that the 4713 line behaves

TABLE 5

DOPPLER DISPLACEMENTS OF LINES FROM POSITION ANGLE A RELATIVE TO POSITION ANGLE B

Line	$\delta\lambda$ (A)	v (km/sec)	Ion	Mean v (km/sec)
He II, 4686	0.08	5.1	He II	5
He I, 4388	.01	0.7	He I	5.5
4471	.09	6.0		
4713	.19	12.0		
Ti II, 4550	.78	51	Metals	50
4572	.80	53		
Ba II, 4554	0.71	47		

in a different way from the λ 4471 line; in this case it is more "metal-like." We have previously (Paper IV) noticed this individual behavior of the 4713 line. This circumstance may open up an interesting avenue along which to pursue the study of the helium-excitation conditions in prominences and flares, if the lines are formed in the same region. The two determining factors for the excitation are the density and the temperature. These will influence the different helium lines in different ways. If one therefore determines how different lines will be influenced by changing T and n_e, a systematic study of helium-line intensity ratios and their variations in prominences and flares may, in turn, give valuable information on these two determining factors. We further note that the emission from He I, 4388 is virtually a straight line perpendicular to the dispersion, i.e., $\delta\lambda \approx 0$. This is the only singlet line observed, and we can therefore not study an indicated possible difference between the emission from the singlet and triplet helium lines.

The great difference in the $\delta\lambda$ values is between the helium lines and the metal lines. This shows that different parts of the surge exhibit different excitation conditions. From completely new arguments we therefore conclude that this surge is built up of regions where the physical conditions differ from one region to another. What we have called part A of the surge consists of at least two "subsurges." In the first, the excitation conditions are such that helium emission dominates, and in the other they favor emissions from singly ionized metals.

In the case of loops we witness a gradual cooling-off of the prominence material and hence the development of different regions giving rise to the different line emissions. The same may be true for some surges. But in the present case the different excitation regions—the "subsurges"—seem to be shot out simultaneously from the flare region. The complex excitation conditions are hence created by the "explosion," not primarily as a result of the cooling-off of the material.

There are at least two ways to explain why the excitation conditions are such that the metal lines do not show up in the region between position angles A and B, viz., (1) the temperature is too high, and (2) the density is too low.

Careful tracings of the spectra show that the He II emission (λ 4686) comes mainly from the region between position angles A and B. This, in itself, points strongly to a high temperature of that plasma. Furthermore, the intensity of the He I emission is stronger from the region between A and B than from position angle A, indicating that the density in that region is quite high compared with what it is in part A. If this picture is correct, the absence of the Ti II, Fe II, and Ba II emission lines in the region between A and B should be due to the high temperature there.

TABLE 6

SPECTRAL CLASSES IN SOLAR ATMOSPHERE

	Class			
	I	II	III	IV
Criteria.....	Strong metals Weak He	He I, 4026≈Sr II, 4078 or: He I, 4713≈Ti II, 4572 He II, 4686≪He I, 4713	He I, 4026≫Sr II, 4078 or: He I, 4713≫Ti II, 4572 He II, 4686≈He I, 4713	Coronal lines
Examples..	Low chromosphere	Chromosphere at 1500 km Quiescent prominences (including the *disparition brusque* phase)	High chromosphere (spicules) Active prominences (loops, surges) and flares	Corona

V. CLASSIFICATION CRITERIA

It was mentioned in Section II that the Fe II emission in the surge of November 18, 1960, was very faint relative to the Ti II emission. We have studied a number of prominence spectra to determine whether this faintness of the iron lines is characteristic of active prominences, and it seems to be the case. On the other hand, the ionized-iron emission is always strong in flares whose spectra show emission in the metal lines. This leads us to reconsider the problem of classifying prominences and flares by their line emission.

A spectral classification of solar atmospheric objects was given in Paper IV, Table 4. We reproduce this table here as Table 6, and we shall concern ourselves with classes II and III.

The philosophy behind this classification is based on a picture of prominences and flares where these objects are built up of different regions. Some regions are fairly cool ($\approx 10^4$ ° K) with strong hydrogen and metal-line emission, while the helium emission is weak. Others are composed of a rather hot plasma (several times 10^4 ° K) with strong helium and faint metal-line emission. A comparison between the "classification lines" gives a measure of which regions dominate a given object. This, then, is the simple classification of Table 6.

We could also have used the emission from other abundant metal ions (e.g., Fe II) to make the comparison with the helium region. It will be recalled that Waldmeier (1951) introduced a classification in which he compared the emission from the Mg I, b-lines with the Fe II, b_3-line, λ 5169 A. His class I is defined by the criterion that the Fe II, b_3-line is weaker than the weakest line of the Mg I triplet ($b_3 < b_4$). As the b_3-line intensity increases relative to the Mg I triplet (whose line intensities are in the ratios $b_1:b_2:b_4 = 5:3:1$), the classification takes us from class I to class V($b_3 > b_1$).

When we intercompare objects classified by Waldmeier's method and ours, we find a systematic difference. In our classification, active prominences and flares are classified together, showing that both types of objects are spectroscopically very active, exhibiting high-excitation conditions. While this emphasizes the fact that it is often difficult to decide whether a given object is a limb flare or a very active, brilliant prominence, it also shows that the simple classification is unable to cope with such subtleties. In Waldmeier's

TABLE 7

LINE INTENSITIES IN FLARES AND ACTIVE PROMINENCES AS COMPARED WITH QUIESCENT PROMINENCES AND CHROMOSPHERE

Line (λ)	Ion and Mult. No.	Flares		Active Prominences			Quiescent Prominences		Chromosphere
		Aug. 14, 1958	Oct. 13, 1958	Dec. 19, 1956	Dec. 30, 1956	Dec. 12, 1957	Dec. 30, 1958	Sept. 16, 1958	
4686	He II 1	80	100	115	15	20	1	1	3
4922	He I 48	....	....	85	5	20	6	2	6
4713	12	100	100	100	25	50	10	8	10
4924	Fe II 42	....	....	Tr.*	0.5	2	10	6	11
4584	38	10	10	0	0.5	2	3	6	3
4508	38	3	....	0	0	0	1	1	....
4629	37	3	8	0	0	0	0	0.5	....
4555	37	5	4	0	0	0	0	0.5	....
4572	Ti II 82	6	1	10	10	10	10	10	10
4564	50	4	2	8	10	8	10	11	8
4534	50	4	....	8	10	8	10	10	9
4501	31	2	....	2	7	7	10	10	9
4468	31	....	....	Tr.	5	8	10	10	11
4554	Ba II 1	2	0.5	5	5	5	11	10	11

* Tr. = trace.

classification, flares belong to his class IV or V, which we might consider to be at the extreme active end of his classification scheme. Quiescent (stationary) prominences belong mostly to class III, while sunspot prominences (active) are classified as of class I or II. Hence Waldmeier's classification, based on the intercomparison between different metal lines only, leads to a spectroscopic distinction between active prominences and flares. Since this is not the case in our classification, we shall consider the necessity for finer classification criteria.

In Table 7 we give line intensities (measured or estimated on Climax spectrograms) from flares and active prominences as seen at the limb and compare them with the data in quiescent prominences and in the chromosphere at a height of approximately 1500 km (Athay and Menzel 1956; Zirker 1958). To facilitate the comparison, the intensity of the Ti II, 4572 line is arbitrarily set equal to 10 in prominences and in the chromosphere, while the intensity of the Fe II, 4584 line is set equal to 10 in flares.

First, we satisfy ourselves that the line-intensity ratios in quiescent prominences follow those in the chromosphere (see also Paper IV). Second, we notice that, in the active prominences studied, the Ti II emission is decidedly stronger than the Fe II emission;

whereas, in flares, the Fe II emission equals or exceeds the Ti II emission. Our material is admittedly limited but, even so, strongly suggests that the intensity ratio between a suitable Fe II line and a Ti II line be used as a criterion to distinguish between limb flares and active prominences.

Since the other "classification lines" in the blue-green region lie around 4600 A, it seems natural to choose the 4584 line of Fe II (multiplet 38), together with the 4572 line of Ti II.

We thus introduce the line-intensity ratio $M = I(4584)/I(4572)$ and classify an active limb event as a prominence if $M < 1$ and a flare if $M \geq 1$

All our data refer to limb observations, and few pertinent data on disk flares are found in the literature. For the disk flare of September 18, 1957 (Jefferies, Smith, and Smith 1959), actual line intensities are not given. The emissions are divided into three categories: faint, moderate, and strong. Of the lines in Table 7, all are called faint, except Fe II, 4584, which is moderate, and the lines of multiplet No. 42 of Fe II, which are all strong. Further, in a flare observed by Allen (1940), the Fe II, 4584 line was 30 times stronger than the 4572 line of Ti II. Richardson observed a flare near the limb in 1947 (Richardson 1950), and there the M-value was 6.

Now caution should be exercised when we compare line-intensity ratios in objects seen above the limb with measurements in disk flares. The ratio between lines from the metal region and the helium domain is quite different in limb and disk flares. This is due to the strong background in the latter, against which the helium lines sometimes are nearly lost. But a straightforward comparison between lines of Fe II and Ti II should not meet with this difficulty.

The only clear-cut case we have found where the M-criterion broke down was a prominence observed by Richardson in 1946. There the M-ratio was 2 (the intensities on a relative scale being 6 and 3), but the excitation conditions must have been quite extraordinary, inasmuch as the Fe II, 5169 line had an intensity of 20. This was a limb event, and we would have classified it a flare; Richardson called it a "prominence." Now it is often difficult to decide whether a limb event is a flare or an active, brilliant prominence. This is due to the main flare criterion adopted being a brightness measure, which is difficult to evaluate for an object at the limb.

It may also be that a flare develops into a prominence or vice versa. The surge of November 18, 1960, was seen to be shot out of a flare and exhibit definite prominence characteristics ($M < 1$). Unfortunately, we do not have spectra of the flare. An interesting set of observations which may, however, have caught the "transition phase" of a prominence into a flare was made during a limb event on August 14, 1958. A surgelike prominence developed around 1420 U.T. and was reported to reach flare intensity. We have spectra taken with 4-minute intervals during the development of this object, at 1422 and 1426 U.T. From the 1422 U.T. spectra, we measure the M-ratio to be 0.6, with an indication that M is greater at lower heights. It is as if the "flare character" of the object is more pronounced in its lower parts or, stated differently, as if a "flare excitation" is coming from below. As the object developed, the selective excitation of Fe II increased markedly relative to Ti II, and at 1426 U.T. the ionized-iron emission was decidedly stronger than the Ti II emission. We observed at that time an M-value of 1.2. Judged by our criterion, we would say that the surge prominence had developed into a flare.

It might have been interesting to use an Fe II line of multiplet No. 42 instead of the line of multiplet No. 38 as classification line, since this is what Waldmeier does. The lines in question would be either λ 4924, 5018, or 5169 A. In a few cases where the 5018 A line was used, the resulting classification was that to be expected from other metal-line criteria (Tandberg-Hanssen 1960). However, in one case the line 4924 A behaved quite unexpectedly. We shall examine what happened to this line in the spectra of the surge of December 19, 1956.

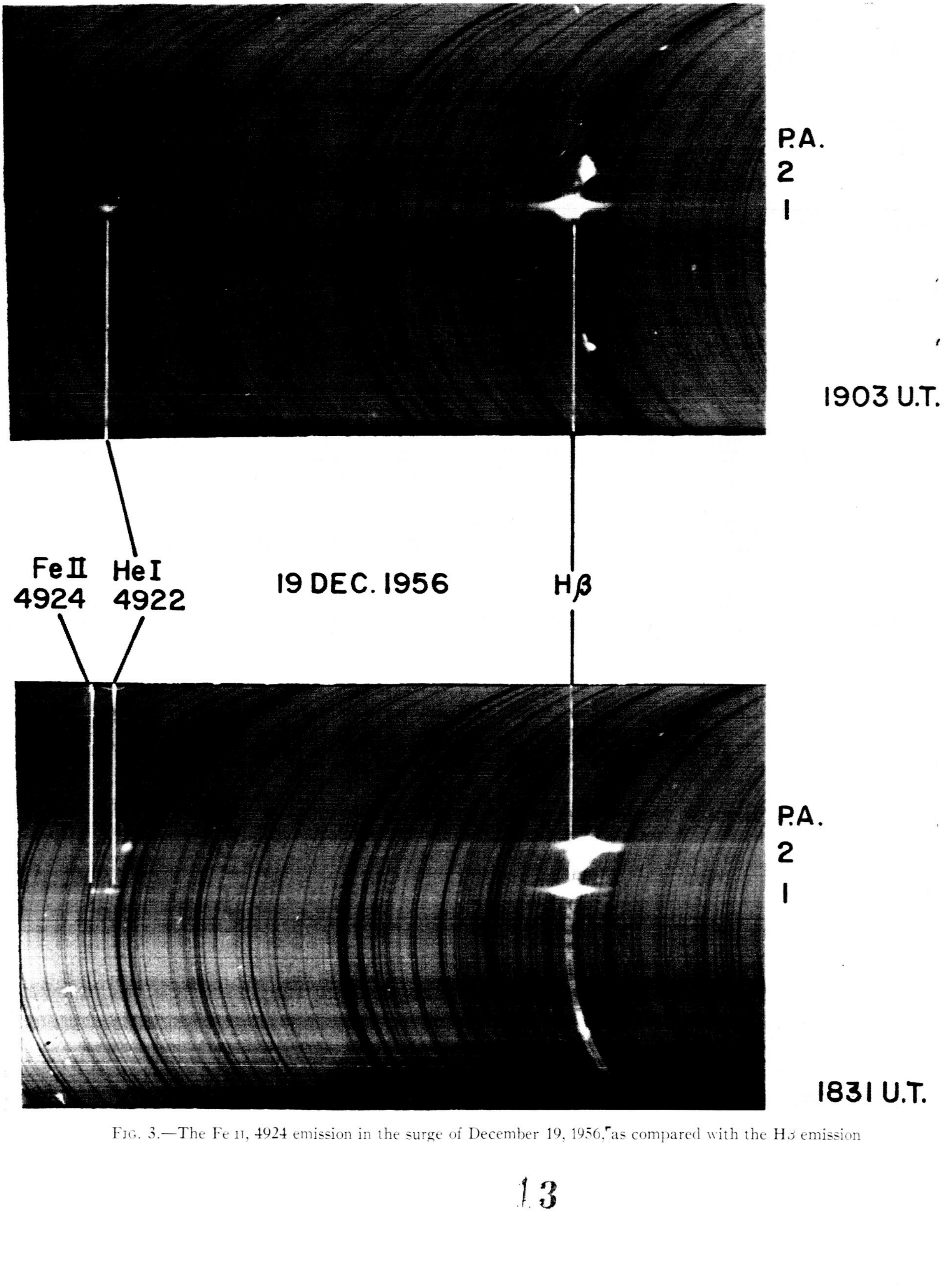

FIG. 3.—The Fe II, 4924 emission in the surge of December 19, 1956, as compared with the Hβ emission

The surge was very active and of great brilliance, at times reaching flare intensity. The very broad He II line, 4686 A, points to an extreme degree of excitation, and the metal lines are nearly "burnt out." They can, at times, nevertheless be seen quite distinctly, and their change in intensity follows closely that of the hydrogen Hβ line, with the outstanding exception of Fe II, 4924. The surge consisted of two parts, position angles 1 and 2. At 1831 U.T., position angle 2 showed the stronger emissions in all lines (of hydrogen, helium, Ba II, and Ti II), except in the Fe II, 4924 line (see Fig. 3). This line is virtually absent in position angle 2, while it is quite strong in position angle 1, equaling the He I, 4922 line in central intensity. All other metal lines, also other multiplets of Fe II, are extremely weak or absent in position angle 1 (see Paper III for additional illustrations). Half an hour later, at 1930 U.T., when position angle 1 has strengthened all its emissions and when, for instance, the Ba II and Ti II lines are easily visible, the Fe II, 4924 line has all but disappeared.

This behavior is not paralleled by any other Fe II line in the wavelength region studied, i.e., multiplets 37 and 38, and the question arises why the multiplet 42 line shows this unexpected change. Evidently some sort of selective excitation process is made possible under certain conditions in prominences or flares. We shall shortly return to this question.

VI. EXCITATION OF Ti II AND Fe II LINES

In comparing Waldmeier's classification and ours, we are faced with two questions: (1) Why do the Fe II and Ti II lines behave differently in flares and in prominences? and (2) Is there a special selectivity for exciting the lines of multiplet No. 42 in Fe II to be taken into consideration? We are thus led to consider "the Fe II–Ti II anomaly," so well recognized in stellar spectroscopy (see, for example, Struve 1951) but, to the best of our knowledge, not considered by solar physicists. We may gain information by a comparison with certain stellar spectra and shall briefly discuss some aspects of the stellar Fe II–Ti II problem.

Although the overwhelming majority of stars show pure absorption-line spectra, there is a fair number where emission lines are found superimposed on a continuous or absorption-line spectrum. In nearly all cases, hydrogen is the dominant element in emission, but also Fe II lines often appear bright, as contrasted to Ti II lines, which are seen only rarely in emission. In most stellar objects where both Fe II and Ti II lines appear bright, the Fe II lines are much the stronger. An outstanding exception is furnished by the irregularly variable, late spectral type, star R Corona Borealis (Herbig 1949). When its light faded during the 1948–1949 minimum, the spectrum developed emission lines, mainly of Ti II and Sc II. No hydrogen emission was seen, and there was only one faint Fe II line in emission. This is the striking feature of the emission-line spectra. The absence of hydrogen lines may be an abundance effect, but the Fe II weakness relative to Ti II and Sc II is most probably due to selective excitation effects.

Joy (1945) has pointed out that there is a similarity between the solar chromospheric spectrum and the bright-line spectrum of the T Tauri variable stars. These stars show an absorption line, dwarf spectrum (F5 V–G5 V), superposed on which we find the emission spectrum. We find, however, that, while the strengths of the Ti II and the Fe II emission lines are comparable in the chromosphere, the Fe II lines dominate the spectra of T Tauri stars. A selective excitation mechanism is therefore most likely in operation there also.

When we consider the different multiplets of Fe II, we notice that in some prominences and flares the strongest lines belong to multiplet No. 42. This also applies to the solar chromosphere. In other cases, lines from multiplets Nos. 37 and 38 are much the stronger. Now the lines of multiplet No. 42 are unique in the sense that their upper level, z^6P^0, can be reached directly from the ground state, a^6D (Merrill 1956). The other multiplets, Nos. 37 and 38, have upper levels inaccessible from the a^6D level, unless intersystem transitions are involved. This may possibly account for the great strength with which the lines 4924, 5018, and 5169 sometimes show up in emission, and it should be kept in mind when comparisons are made with Waldmeier's classification. Since, however, the lines of multiplet No. 42 do not always dominate the ionized-iron emission, the accessibility to the z^6P^0 level is in many cases counteracted by other factors (exchange-collisional transitions).

A similar state of affairs is found in the Ti II ion. Of the lines discussed, only those belonging to multiplet No. 41 have an upper level, z^4D^0, directly accessible from the ground level, a^4F. To reach the upper level of the other strong multiplets in this wavelength region (Nos. 31, 50, and 82), intersystem transitions are again required. In the chromosphere, the lines of multiplet No. 41 are not among the strongest Ti II lines or in many prominences. But we have observed prominences where these lines furnished some of the strongest Ti II emission, e.g., a quiescent prominence of December 2, 1956. Also, in the previously mentioned disk flare of September 18, 1957, the lines of multiplet No. 41 were the strongest Ti II lines observed.

TABLE 8

MEASURED $M = [I(4584)/I(4572)]$ RATIOS IN SOME FLARES AND PROMINENCES

Flares		Active Prominences		Quiescent Prominences	
Date	M	Date	M	Date	M
6 Sept. 1939*	33	9 May 1929§	0.3	10 Nov. 1956	0.8
11 Apr. 1947†	6	12 Nov. 1956	.45	30 Dec. 1956	1.0
18 Sept. 1957‡	> 1	19 Dec. 1956	< .1	23 Mar. 1958	0.35
14 Aug. 1958	1.7	30 Dec. 1956	.05	10 Sept. 1958	0.5
13 Oct. 1958	10	12 Dec. 1957	0.2	16 Sept. 1958	0.6

* Disk flare observed by Allen (1940).
† Flare near limb observed by Richardson (1950).
‡ Disk flare observed by Jefferies, Smith, and Smith (1959).
§ Prominence observed by Grotrian (1931).

It would be interesting to undertake a thorough study of the emission spectra of Fe II and Ti II under different excitation conditions to predict the M-ratio. Since the opacities involved are not high, the M-ratio may be written in the form

$$M = \frac{I(4584)}{I(4572)} = \frac{n_2(\text{Fe II})\,A(4584)\,\nu(4584)}{n_2(\text{Ti II})\,A(4572)\,\nu(4572)}\,. \tag{6}$$

Here n_2(Fe II) is the number of Fe II ions in the z^4D^0 level, and $A(4584)$ is the probability for a transition leading to emission of the 4584 line. Similarly, n_2(Ti II) and $A(4572)$ refer to the Ti II line, whose upper level is z^2G^0. The population n_2(Fe II) can be obtained from the combined Saha-Boltzmann equation:

$$\frac{n_2(\text{Fe II})}{n_e n(\text{Fe III})} = \left(\frac{2\pi m kT_e}{h^2}\right)^{3/2} \frac{g(4584)\,b(4584)}{2\,U(\text{Fe III})}\, e^{\chi(\text{Fe})/kT_e}, \tag{7}$$

where g is the statistical weight, $2J + 1$; b is the factor that measures the departure from local thermodynamic equilibrium (LTE); U is the partition function; and $\chi(\text{Fe}) = (16.2 - 5.5)$ ev. A similar equation holds for n_2(Ti II). When we combine the Saha-Boltzmann equations and equation (6), we can express the M-ratio as

$$M = f(T_e)\frac{b(4584)}{b(4572)}\,\frac{n(\text{Fe III})}{n(\text{Ti III})}, \tag{8}$$

where $f(T_e)$ is a known function of the electron temperature.

Table 8 gives observed M-ratios in a number of flares and active prominences as compared with quiescent prominences. If we can estimate the function $f(T_e)$, we obtain $[b(4584)/b(4572)]\,[n(\mathrm{Fe\ III})/n(\mathrm{Ti\ III})] = f(b, n)$. For comparison we note that the chromospheric M-ratio is about 0.8. With an assumed electron temperature $10^4\,{}^\circ$ K in the component emitting the metal lines, we find $f(b, n) = 7$, and the b ratio can be determined, once we know the $n(\mathrm{Fe\ III})$ and $n(\mathrm{Ti\ III})$ values.

Unfortunately, the atomic data involved are in a deplorable state and, for the time being, do not allow us to compute satisfactorily the ionization equilibria of Ti and Fe in non-LTE. Hence, only when reliable ionization computations permit us to evaluate the $[n(\mathrm{Fe\ III})]/[n(\mathrm{Ti\ III})]$ ratio can we, from the observed M-ratio and equation (8), draw conclusions as to the direction and degree of departure from LTE in flares and prominences.

Thanks are due to the staff of the Climax station for obtaining the high-quality spectra used in this analysis. Most of the tracing of the spectra was ably done by Mr. G. Peck. It is also a pleasure to acknowledge stimulating discussions with Drs. Athay, Billings, and Zirin.

This work was supported by the National Aeronautics and Space Administration under contract No. NsG-92-60 with the High Altitude Observatory, Boulder, Colorado.

REFERENCES

Allen, C. W. 1940, *M.N.*, **100**, 635.
Athay, R. G., and Menzel, D. H. 1956, *Ap. J.*, **123**, 285.
Grotrian, W. 1931, *Zs. f. Ap.*, **2**, 106.
Herbig, G. H. 1949, *Ap. J.*, **110**, 143.
Jefferies, J. T., and Orrall, F. Q. 1961, *Ap. J.*, **133**, 946.
Jefferies, J. T., Smith, E. V. P., and Smith, H. J. 1959, *Ap. J.*, **129**, 146.
Joy, A. H. 1945, *Ap. J.*, **102**, 168.
Merrill, P. W. 1956, *Lines of Chemical Elements in Astronomical Spectra* ("Publications of the Carnegie Institution of Washington," No. 610).
Richardson, R. S. 1950, *Ap. J.*, **111**, 572.
Struve, O. 1951, *Astrophysics*, ed. J. A. Hynek (New York: McGraw-Hill Book Co., Inc.), chap. 3.
Tandberg-Hanssen, E. 1959, *Ap. J.*, **130**, 202 (Paper III).
———. 1960, *Astrophysics Now*, **6**, 161.
Tandberg-Hanssen, E., and Zirin, H. 1959, *Ap. J.*, **129**, 408 (Paper I).
Waldmeier, M. 1951, *Zs. f. Ap.*, **28**, 208.
Zirin, H., and Tandberg-Hanssen, E. 1960, *Ap. J.*, **131**, 717 (Paper IV).
Zirker, J. W. 1958, *Ap. J.*, **127**, 680.

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